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‘Slippery slope’ or ‘uphill struggle’? Broadening out expert scenarios of climate engineering research and development

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ABSTRACT

It is increasingly recognised that meeting the obligations set out in the Paris Agreement on climate change will not be physically possible without deploying large-scale techniques for either removing greenhouse gases already in the atmosphere or reflecting sunlight away from the Earth. In this article we report on the findings of a scenarios method designed to interrogate how far these ‘climate engineering’ ideas may develop in the future and under what governance arrangements. Unlike previous studies in climate engineering foresight that have narrowly focussed on academic perspectives, a single climate engineering idea and a restricted range of issues, our approach sought to respond to theoretical imperatives for ‘broadening out’ and ‘opening up’ research methods applied to highly uncertain and ambiguous topics. We convened a one-day event with experts in climate change and climate engineering from across the sectors of government, industry, civil society and academia in the UK, with additional experts from Brazil, Germany and India. The participants were invited to develop scenarios for four climate engineering ideas: bioenergy with carbon capture and storage, direct air capture and storage, stratospheric aerosol injection and marine cloud brightening. Manifold challenges for future research were identified, placing the scenarios in sharp contrast with early portrayals of climate engineering research as threatening a ‘slippery slope’ of possible entrenchments, lock-ins and path dependencies that would inexorably lead to deployment. We suggest that the governance challenges for climate engineering should therefore today be thought of as less of a slippery slope than an ‘uphill struggle’ and that there is an increasingly apparent need for governance that responsibly incentivises, rather than constrains, research. We find that affecting market processes by introducing an effective global carbon price and direct government expenditure on research and development are incentives with broad potential applications to climate engineering. Responsibly incentivising research will involve a pluralistic architecture of governance arrangements and policy instruments that attends to collective ambitions as well as national differences and emerges from an inclusive and reflexive process.

1. Introduction

The Paris Agreement on climate change has set out worldwide, legally binding commitments to keeping the increase in global temperature to well below 2 °C above preindustrial levels and to aim to limit the increase to 1.5 °C. Yet, climate modelling research has projected that meeting these obligations will not be physically possible without deploying large-scale techniques for either removing greenhouse gases already in the atmosphere or reflecting sunlight away from the Earth (Azar et al., 2010; Rogelj et al., 2011; Fuss et al., 2014; Gasser et al., 2015). Indeed, one technique – bioenergy combined with carbon capture and storage – is assumed in many of the Intergovernmental Panel on Climate Change (IPCC) stabilisation pathways. Despite growing recognition of this, these ‘climate engineering’, or ‘geoengineering’, ideas are virtually no closer to resembling the sorts of complete sociotechnical systems – assemblages of technical objects and social arrangements that act together as a single system – that would be needed for deployment than they were more than ten years ago when Nobel laureate Paul Crutzen made his influential call for research (2006).

In this article we report on the findings of an expert scenarios method designed to explore how far climate engineering ideas may develop in the future and under what governance arrangements. It contributes to a small but growing literature on climate engineering foresight designed to help decision makers and others plan for the future (Low, 2016; Sugiyama et al., 2017). Foresight methods including the two-axis scenario method (GAO, 2011; Banerjee et al., 2013), forms of structured scenario planning (Boettcher et al., 2015; Haraguchi et al., 2015; Low, 2017) and modified red-teaming (Milkoreit et al., 2011) have been used to explore various aspects of climate engineering

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governance, including how the ideas may evolve in general (Haraguchi et al., 2015; Banerjee et al., 2013), how research in particular may evolve (GAO, 2011), how early movers might influence governance to their advantage (Milkoreit et al., 2011), what effects deployment might have on international relations (Boettcher et al., 2015) and how governance might be adapted to account for a wide range of plausible futures (Low, 2017).

We situate our particular approach to climate engineering foresight in relation to theoretical imperatives for 'broadening out' the inputs to and 'opening up' outputs from research methods applied to highly uncertain and ambiguous topics (Stirling, 2008; Bellamy et al., 2012). Inputs can be judged on the diversity of participating perspectives, options considered and issues raised while outputs can be judged on the degree of plurality and conditionality (reflexivity) with which findings are communicated. While some previous foresight methods applied to climate engineering have engaged with a diversity of participants from across government, industry and civil society (GAO, 2011; Haraguchi et al., 2015), most have only narrowly engaged with academics. With the exception of the scenarios exercise convened by the US Government Accountability Office (2011) which examined non-specific climate engineering, all previous studies have focussed on stratospheric aerosol injection – an idea to reflect sunlight away from the Earth using reflective aerosols – at the expense of a symmetrical treatment of alternatives. While most previous studies involved identifying a broad range of axes and uncertainties that might characterise climate engineering futures, all involved narrowing those down to only a handful of issues. With the exception of one previous study that sought to prescribe unitary policy recommendations (Haraguchi et al., 2015), all were otherwise relatively reflexive in the communication of their findings.

2. Method

Our method sought to continue the tradition of reflexive reporting while at the same time substantially broadening out the diversity of participating perspectives, options considered and issues raised. We convened a one-day scenarios workshop in London with international experts and stakeholders in climate change and climate engineering from across the sectors of government, industry, civil society and academia, drawn primarily from the United Kingdom, but with individual representatives from Brazil, Germany and India (see Table 1). The participants were divided into four heterogeneous groups and each invited to consider two of four climate engineering ideas selected by the research team for their operational diversity and policy relevance. These included two greenhouse gas removal (GGR) ideas: bioenergy with carbon capture and storage (groups 2 and 4) and direct air capture and storage of carbon dioxide (groups 1 and 3); and two sunlight reflection method (SRM) ideas: stratospheric aerosol injection (groups 3 and 4) and marine cloud brightening (groups 1 and 2). Our purpose in developing two scenarios, by two different groups, for each climate engineering idea was to explore uncertainties and ambiguities, to be represented as divergences between the groups' scenarios. In doing so, we hoped to generate a richer array of possible trajectories for the development of climate engineering ideas. In turn, this was to allow us to identify a more diverse set of factors under which the ideas might advance or fail.

Table 1
Scenarios workshop participants.

Code	Group	Occupation
P1	1	Manager at a British innovation consultancy firm
P2	1	Engineering scientist at a British university
P3	4	Deputy head of legal affairs at a Brazilian Government department
P4	2	Chief executive officer at an Indian policy research institute
P5	3	International relations scholar at a German university
P6	1	Marine policy advisor at a British Government department
P7	2	Portfolio manager at a British Research Council
P8	1	Environmental scientist at a British university
P9	3	Climate engineering lead at a British Government department
P10	4	Climate science advisor at a British Government department
P11	2	Freelance British environmental researcher
P12	4	Researcher at a German sustainability research institute
P13	3	Deputy head of strategy at a British Research Council
P14	3	Senior scientist at an international environmental NGO
P15	2	Science and technology studies scholar at a British university
P16	4	Marine scientist at a British marine research centre

The groups were also asked to consider four idealised governance models: self-regulation by climate engineering scientists, engineers or entrepreneurs; global governance (an international agreement for harmonising the conduct of research across countries); principles and protocols (a step-by-step, 'bottom-up' approach to governance); and moratoria to proscribe particular ideas or activities: if, when, and how each might play a role.

By way of preparation, the participants were given access to selected influential writings related to these models in advance, respectively: Keith (2013); Bodle et al. (2014); Rayner et al. (2013) and Hulme (2014). Each group was asked to develop a timeline and narrative storyline for climate engineering research over the next twenty years, considering major events in both the development of the ideas and in their governance. The participants were invited to choose between a forecasting approach (beginning with a 'starting point', and exploring how governance might respond to events) and a backcasting approach (beginning with an 'end point', and exploring how governance may shape events) to the exercise. In practice, all groups opted for the forecasting mode, as they felt that backcasting was too linear and one that required group consensus on an end point from the outset. They were also asked to consider possible branching points where timelines might change course. The groups were facilitated by members of the research team and scribes made detailed qualitative notes on the deliberations. We then undertook observational content analysis whereby themes of discussion were defined during data analysis and derived from the data itself, rather than from external theories, research or interests (Hsieh & Shannon, 2005). Each group also produced a diagrammatic representation of their scenarios (see Figs. 1–4).

In the next two sections we report on the scenarios produced for the four climate engineering ideas under consideration, starting with GGR ideas in section three and SRM ideas in section four. In section five we then discuss the findings in relation to those of other foresight studies and the broader context of climate engineering governance before in section six reflecting on the limitations of our approach and offering plural and conditional recommendations to policy makers for responsibly incentivising research.

3. Scenarios for greenhouse gas removal

3.1. Bioenergy with carbon capture and storage (BECCS)

BECCS is an idea that couples biomass energy generation with carbon capture and storage (CCS) technology to store the carbon dioxide produced in underground geological formations (Gough & Upham, 2011). Scenarios for BECCS were developed by groups 2 and 4.

Group 4 began by noting that BECCS posed a distinctive definitional challenge: it was a combination of two separate ideas put end to end – bioenergy and carbon capture and storage – but one that was not yet fully demonstrated as a single, integrated technology. It was not clear whether, when, and at what scale it could be considered as a climate engineering technology. Group 2 argued that it amounted to putting two already unpopular technologies together, making its eventual uptake doubly unlikely. This was compounded, they argued, by there being very little political lobbying for BECCS, despite its influential role in the IPCC's stabilisation pathways. Indeed, the mismatch between political will and its policy saliency could be seen in the relatively low levels of funding being directed to BECCS research and development (R

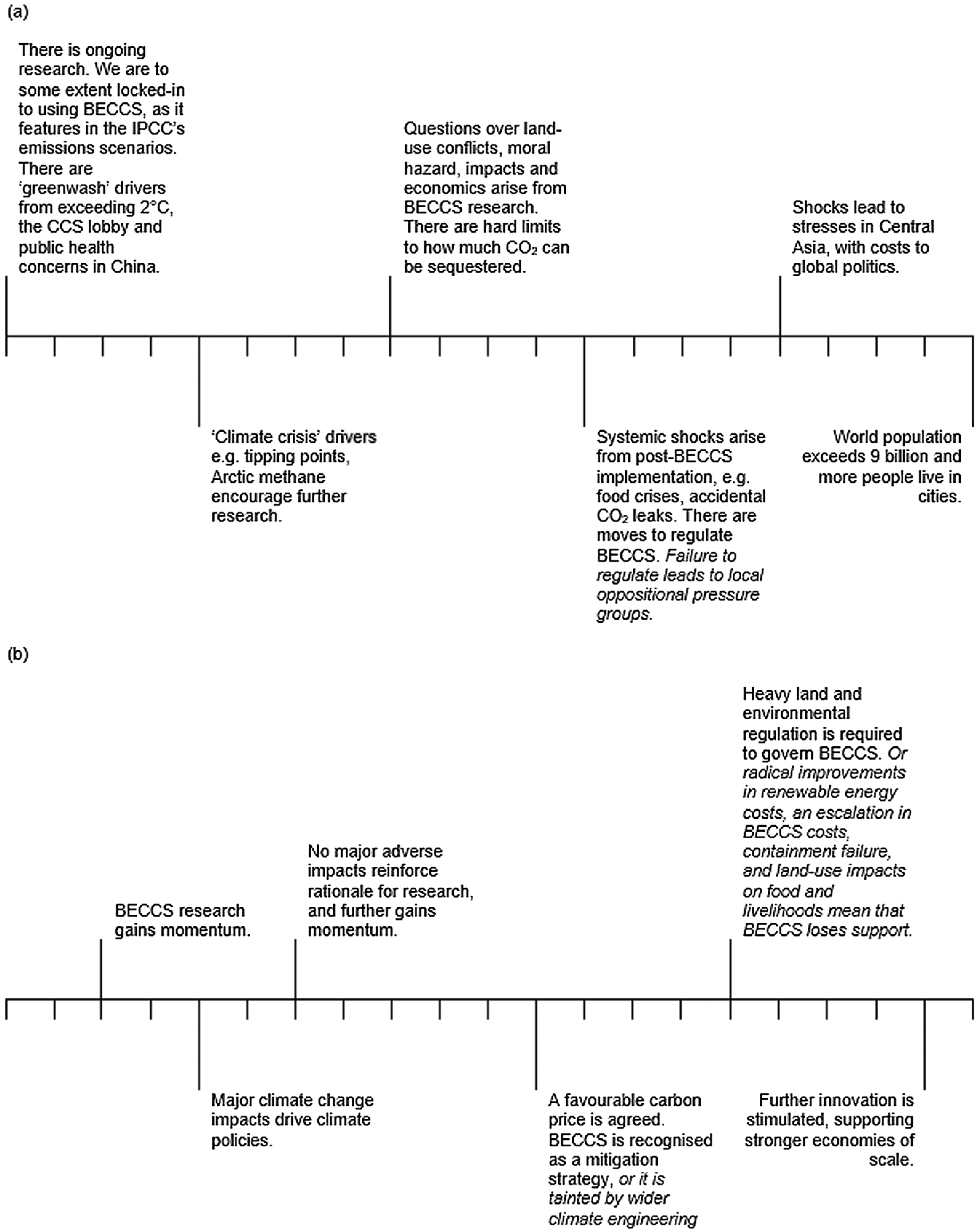

Fig. 1. Group 2 (panel a) and 4 (panel b) scenarios for bioenergy with carbon capture and storage. Time passes from left to right. Each marker along the timeline represents one year. Text in italics denotes possible scenario branching points.

&D). The group therefore raised the question: given an environment in which few researchers were attempting to assess BECCS holistically, and the shortage of research funds, would the research community be likely to survive in confronting any significant major technical or social challenges or setbacks?

Both groups had a similar perspective on technical challenges facing BECCS, albeit with differing emphases. For Group 2, this was the challenge of ensuring a sustainable supply of biomass. They also referred to the UK's White Rose project, a now abandoned plan to develop commercial scale CCS operations at the Drax coal-fired and wood pellet biomass power station, as having had the potential to be a significant technical test of BECCS. Its aim to have tested undersea storage, however, was seen as infeasible. For Group 4, the technical challenges facing BECCS surrounded developing the necessary infrastructure at scale and the safety and effectiveness of underground storage. Efforts in Germany, it was noted, were concentrating on capture but not on storage.

Group 2 saw a potential resource scarcity crisis as critical to the

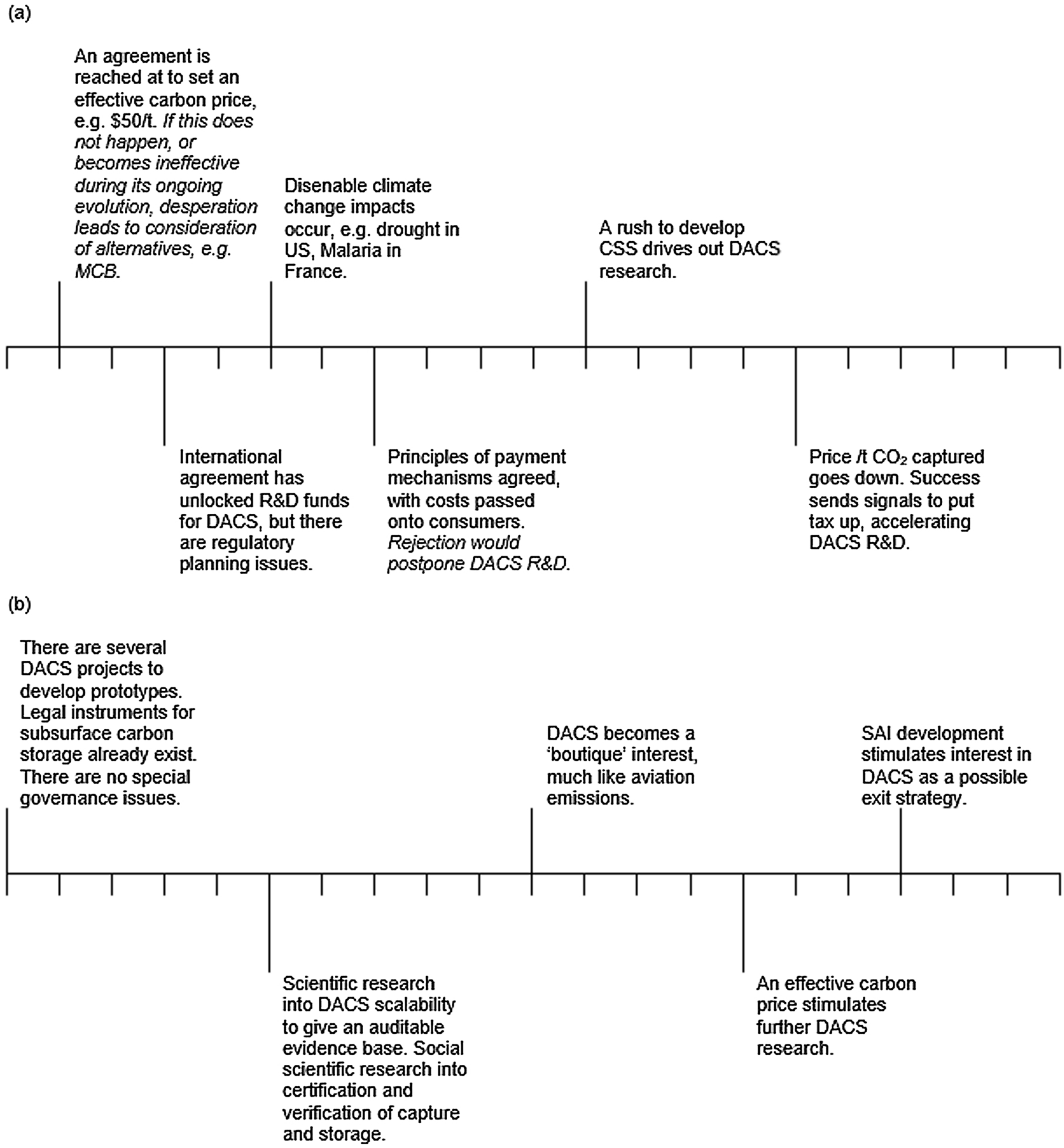

Fig. 2. Group 1 (panel a) and 3 (panel b) scenarios for direct air capture and storage development. Time passes from left to right. Each marker along the timeline represents one year. Text in italics denotes possible scenario branching points.

development of a narrative around BECCS, with the peak of global population recently having been revised upwards in some forecasts from 9 billion to 11 billion by 2100 (see Gerland et al., 2014). Under such circumstances the group felt that the possibility of even 10% of underused land capacity being made available for BECCS was unlikely. A great deal of uncertainty about the trade-offs in land use centred on possible dietary changes that might make more land available and the use of urban areas as possible sites of food production. In this light, the group considered BECCS to be a short-term measure only, and one that could only be a partial contributor to any climate engineering efforts. The group also pointed to biochar – a different climate engineering proposal that would pyrolyze and bury biomass – as an alternative use of biomass that could bring co-benefits to land productivity and agriculture.

The two groups had quite different perspectives on how BECCS would play out over the next twenty years. Group 4 envisaged that the Paris Agreement would lead to an effective global carbon price in 2025. This, they suggested, would incentivise R&D by the private sector. The group caveated that the significance of this occurrence could be tempered by a number of other factors, including (1) the regulation of global land use, which could affect the energy sources, (2) the development of alternative energy sources, and (3) the catastrophic failure of BECCS technology. If the carbon price were not achieved, they understood that research funding would be left in the hands of states (with the possible exception of undersea storage operations), and would continue without significant growth, while still being at risk of regulatory limitations, changes in energy policy and technical failures.

On the other hand, Group 2 did not envisage an effective carbon price resulting from the Paris Agreement. Instead, and in line with the decentralised and gradualist principles and protocols approach to governance, they saw local geopolitical priorities establishing a variety of different prospects for BECCS around the world. Under this view, they considered it might be difficult for BECCS to gain traction in Europe with its already intensive land use. China, on the other hand, as

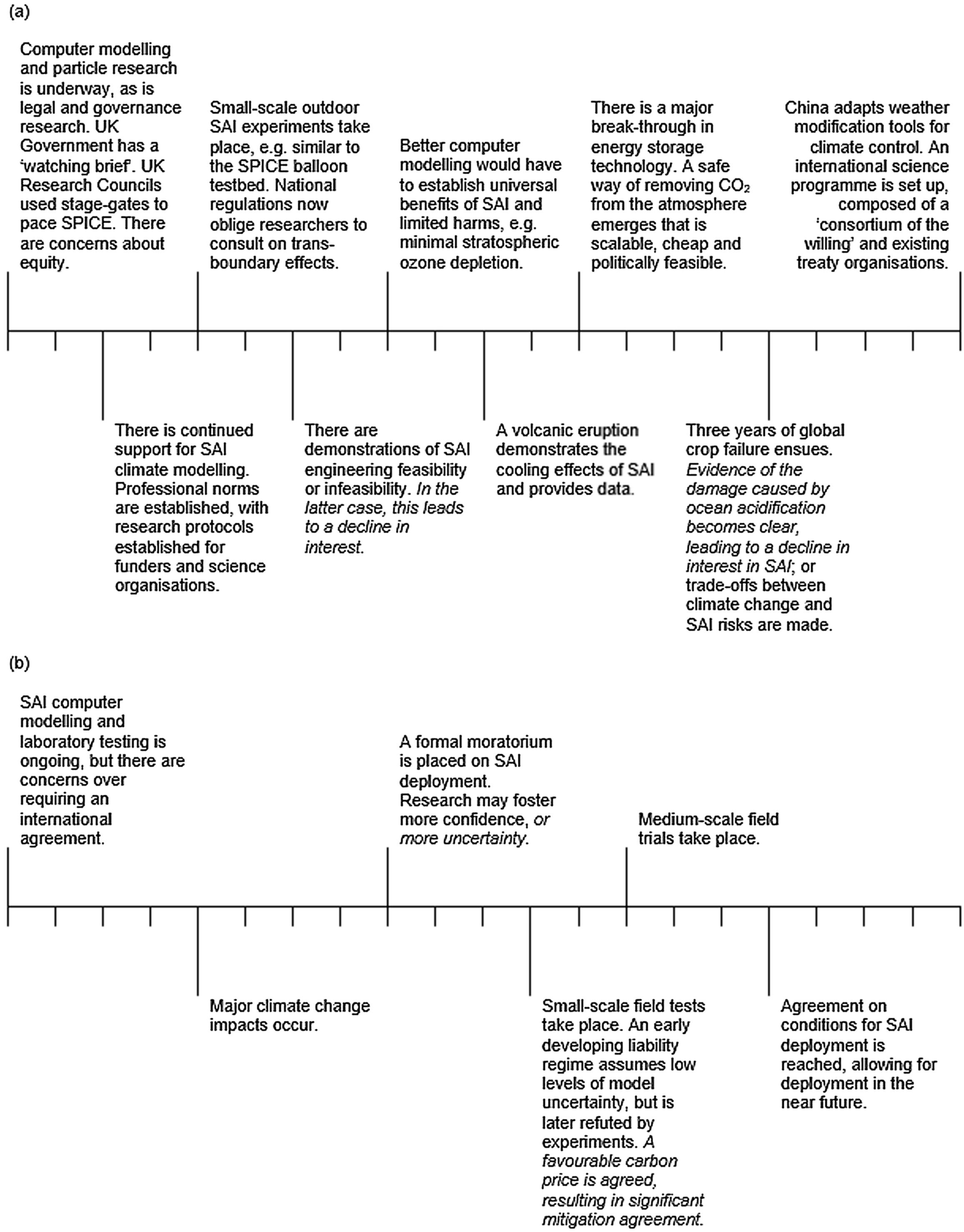

Fig. 3. Group 3 (panel a) and 4 (panel b) scenarios for stratospheric aerosol injection. Time passes from left to right. Each marker along the timeline represents one year. Text in italics denotes possible scenario branching points. Acronym: Stratospheric Particle Injection for Climate Engineering project (SPICE).

a country with a large amount of underused land, was cited as one which might be much more receptive. BECCS, the group suggested, could be used to keep their coal-fired power stations running longer, while the political system in China was also aired as being potentially more amenable to BECCS. India was also identified as a potentially more receptive country, but one which would have to square such developments with democratic traditions. Concurrent advances in biofuel genetic modification were seen as possible developments that might support BECCS in the future, while research into BECCS itself was seen as unlikely to reveal any problems that would kill off the idea. On the other hand, a global food crisis or perceived climate crisis, such as the disappearance of Arctic sea ice, was seen as a risk to BECCS' endurance.

3.2. Direct air capture and storage (DACS)

DACS is an idea for the industrial capture of carbon dioxide from ambient air to be stored in underground geological formations (Keith et al., 2006). Scenarios for DACS were developed by groups 1 and 3.

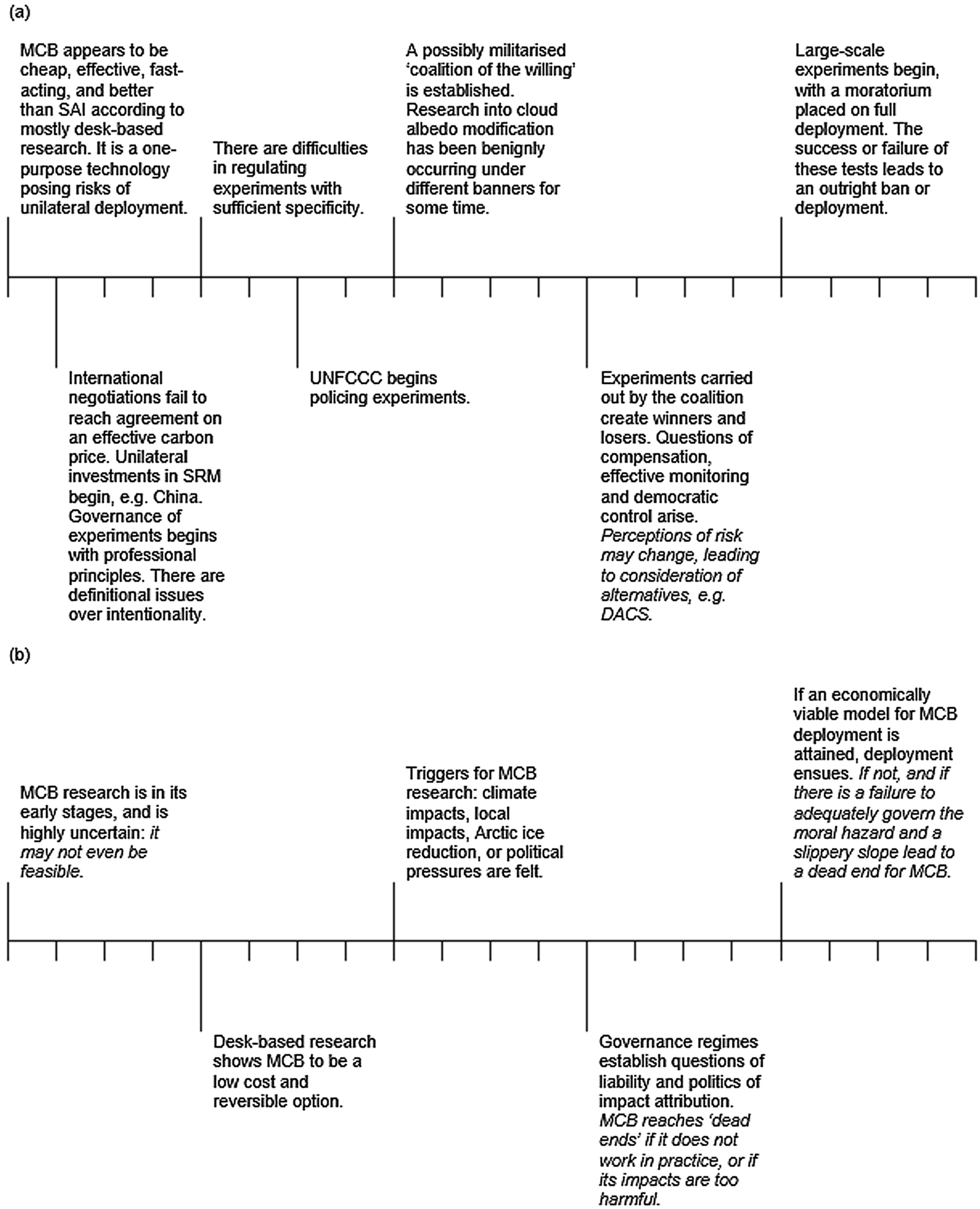

Fig. 4. Group 1 (panel a) and 2 (panel b) scenarios for marine cloud brightening. Time passes from left to right. Each marker along the timeline represents one year. Text in italics denotes possible scenario branching points.

Both groups questioned whether DACS should, or could, ever become preferential to flue-gas carbon capture and storage. Whilst DACS would capture highly diffuse carbon dioxide from the ambient air, CCS would capture the gas from far more concentrated point-sources, thus making DACS a far more expensive prospect than CCS, in terms of $/t CO_2 captured. Moreover, both groups believed that the only sensible energy source for powering DACS would be some form of renewable energy. The question thus arose: if renewable energy became sufficiently economically palatable, why not simply prevent the release of carbon dioxide in the first place by mitigating climate change through renewable energy? In competition with both CCS and renewable energy alternatives then, the groups were sceptical of the uptake of DACS. Yet, the groups also recognised that such approaches would neglect accumulating historical emissions of carbon dioxide already in the atmosphere.

Both groups saw the creation of an effective, globally agreed carbon price as critical to determining the future trajectory of DACS. It would provide the necessary fiscal stimulus for further DACS R&D. Both groups were, however, sceptical as to when such an agreement might be realistically reached. Indeed, Group 1 noted 'difficult partners' in some nations and the temptation of 'free-riding' that might impede progress. While Group 1 assumed the agreement on an effective carbon price

might occur soon, for Group 3 it was not envisioned until at least ~2028. Nevertheless, until the time that an agreement could be reached, DACS R&D was viewed as likely to remain a 'boutique' interest.

The two groups did, however, note some possible alternative routes to incentivising DACS R&D. Group 1 believed that the occurrence of significant climate change impacts might provide motivation. Alternatively, Group 2 believed that the prospects for corporate reputational benefits could stimulate market demand for R&D. The possibility for concurrent development of a sunlight reflection climate engineering proposal, such as stratospheric aerosol injection, might also stimulate interest in DACS as an 'exit strategy' to avoid termination effects. Moreover, carbon dioxide regulation was seen more likely to induce larger reductions in emissions than pricing, thus questioning the imperative for an agreement in the first place.

For Group 1 the governance of DACS was indistinguishable from the governance of climate itself, sharply contrasting with their view on the governance of sunlight reflection climate engineering which was more focussed on the technology proposals themselves. 'NIMBY' public opposition was seen as the most likely challenge for DACS governance by Group 1. On the other hand, DACS was seen as posing 'no special governance issues' by Group 3, who claimed that lessons could be learned from its CCS counterpart. Yet, at the same time, it was seen to represent something of a regulatory paradox in that whilst the proposed technology would operate within national boundaries, it would pose, or even require, transnational effects. The European CCS Directive, they explained, sets requirements for storage and monitoring. An equivalent, 'International Air Capture Agency' could help to build trust through an accounting system with a reporting requirement.

4. Scenarios for sunlight reflection methods

4.1. Stratospheric aerosol injection (SAI)

SAI is an idea for injecting reflective particles, often sulphate, into the lower stratosphere to reflect a proportion of sunlight away from the Earth (Crutzen, 2006). Scenarios for SAI were developed by groups 3 and 4.

Both groups expressed concerns over the uncertainties and potentially harmful consequences of pursuing SAI. They noted that whilst the proposed technology has appeared to be both effective and cheap in many early assessments, these conclusions were based on highly questionable assumptions. Harmful impacts on agriculture and the wider environment raised significant concerns; as did the proposal's failure to address ocean acidification; its potential for fostering a moral hazard whereby mitigation efforts would be diminished; the need for justly compensating those affected by harms; and the risk of a 'termination effect' whereby sudden cessation would bring about rapid rise in temperature commensurate with background levels of unmitigated atmospheric carbon dioxide. For Group 4 these issues were considered reasons strong enough to rule out SAI as an option for tackling climate change, and to doubt that SAI would ever be used. They nevertheless felt that research would, and indeed perhaps should, continue. Group 3, on the other hand, argued that further SAI research would not increase knowledge, but uncertainty.

Both groups saw collaborative international efforts as key to determining the future trajectory of SAI, albeit in different ways. With a de facto moratorium on SAI deployment through the lack of such an agreement at present, they would provide the necessary stimulus for further SAI R&D. For Group 3 this meant either reaching an international agreement on research and deployment; reaching an international agreement on conventional emissions-reduction mitigation efforts, and thereby providing some optimism for another agreement, or looking to 'buy time' until mitigation effects kicked-in; or heeding the international perceptions of research, be they of negatively 'meddling' with the Earth, or positively 'curing' the Earth. For Group 4 it meant the formation of a multilateral 'coalition of the willing'. Such a coalition was seen as likely to form around a specific environmental objective, such as reversing losses to the Greenland ice-sheet. Nevertheless, Group 4 also noted that a distinct risk of unilateralism remained. For example, a small-island state at risk of sea-level rise was seen as potentially likely to deploy SAI as a symbolic act of civil disobedience to draw attention to its plight. Moreover, China was noted as particularly capable of deploying SAI by itself at short notice if desired, owing to its existing advanced weather modification programmes.

The two groups both felt that SAI research would endure in the immediate to mid-term, with a continued focus on computer modelling and governance considerations. In the mid- to long-term the groups believed that research could advance more quickly in response to harmful impacts of climate change. Any deployment of SAI was seen as likely to be met with the establishment of a formal international moratorium. Group 4 considered issues of attribution and compensation for inequitable climatic consequences of deploying SAI to be a substantial challenge. For example, even the need to consider compensation payments for poor equatorial countries affected by sharply changed patterns of precipitation might be sufficient to challenge the culture and values of international development and prevent some governments from pursuing SAI R&D. Moreover, the possibility of 'counter-geoengineering' raised significant concerns for geopolitical stability.

Whilst an international agreement was viewed as the most suitable governance regime for controlling SAI R&D in Group 3, Group 4 noted that their still multilateral 'coalition of the willing' might be governed in different ways. The scale of experimental research was considered to be one such point of debate. For example, should a small-scale experiment in Arizona be governed under the Environmental Protection Agency (EPA) or would it require international assent? The London Convention, adapted for ocean iron fertilisation, was considered an appropriate analogue for experiments conducted within territories being subject to territorial regulation. An equivalent regime for the atmosphere was considered, but it was noted that such a regime should account for social and political impacts as well as physical ones. Moreover, the latter should account for novel environmental impacts, such as ozone depletion. It was, however, unclear as to which organisation would be in a position to establish such a regime. Nevertheless, the group revealed little enthusiasm for giving the UN Convention on Biological Diversity (CBD), which adopted a non-legally binding moratorium on climate engineering activities, further powers in this regard.

4.2. Marine cloud brightening (MCB)

MCB is an idea for brightening marine stratocumulus clouds and thereby making them more reflective by seeding them with sea salt particles (Latham et al., 2012). Scenarios for MCB were developed by groups 1 and 2.

Both groups agreed that MCB represented a particularly immature idea that required much more extensive assessment as to its effectiveness and wider impacts, especially those on precipitation. Both groups also saw potential problems of attribution and liability, particularly for larger scale tests, in the case of weather patterns in one country being affected by those of another using MCB. To illustrate, Group 2 drew attention to issues of distributional justice that are already raised today between provinces in China in relation to weather modification activities. However, Group 2 also expressed beliefs that climate models might already be at their limits in terms of predicting the impacts of MCB. It was also felt that MCB would play into so-called 'chemtrail' conspiracy theories which could influence public discourse more widely. On the other hand, it was seen as a shorter-lived, potentially cheaper alternative to SAI that also did not contribute to ocean acidification. At the same time, Group 1 was particularly concerned with uncertainties surrounding the size of sea salt particles, which, according to climate models, could lead to a warming rather than cooling effect on the climate system (see Alterskjær & Kristjánsson, 2013). They also

expressed their concerns for the possibility of MCB contributing to a moral hazard.

Both groups saw the ultimate failure of international negotiations, and in particular a failure to determine an effective globally agreed carbon price, as a precondition for any increased attention to MCB and indeed to other sunlight reflection ideas in general. In terms of governing MCB, Group 1 saw a global agreement or a moratorium as equally unlikely approaches. This led them to suggest a scenario whereby broad governance principles might be developed up to 2024, when a ‘coalition of the willing’ might form. The coalition was envisaged by the group as a consortium of powerful nations which would build on broad governance principles and protocols to define a research agenda, conduct experimentation including tests at scale, and define a development path, with the aim of assessing whether MCB might have a role, perhaps around Arctic sea ice. The UN CBD was seen as a possible contributor to the regulation of MCB. Group 2, on the other hand, while also adopting a principles and protocols-based approach, instead viewed the future trajectory of MCB as being research-led, with either technical uncertainties leading to a cessation of activities or promising results propelling the approach forward.

Both groups saw MCB as an idea that could potentially be deployed at local scale only, and, owing to claims of its relatively low costs, therefore a candidate for unilateral action by nation-states. In Group 2′s scenario the possible locus of early action to develop the technology was seen to be more likely to be local coastal communities trying to find ways of alleviating heat stress, for example in California or Australia, or China as a progression from their weather modification programme. Under this local action scenario much of the initial regulatory responsibility was seen to fall to the nations concerned, which might lead to so-called ‘jurisdiction shopping’ from the technology's promoters. Nevertheless, it was noted that there would be additional issues associated with ships deploying the technology in international waters, on which the London Convention and Protocol might rule.

5. Discussion

As we discussed earlier, despite growing recognition that meeting the obligations set out in the Paris Agreement will be all but impossible without some form of climate engineering, the ideas are far from resembling the complete sociotechnical systems that would be needed for deployment. The manifold challenges for climate engineering R&D captured in our scenarios are a testament to this gap between recognition and reality. This inertia is in stark contrast with early portrayals of climate engineering research as threatening a ‘slippery slope’ of possible entrenchments (Collingridge, 1980), lock-ins (Arthur, 1989) and path dependencies (David, 2001) that would inexorably, even if undesirably, lead to deployment and therefore necessitate governance that would constrain research (Jamieson, 1996; SRMGI, 2011; Hulme, 2012; Hamilton, 2013; Stilgoe et al., 2013a,b; Cairns, 2014). We suggest that the governance challenges for climate engineering should therefore today be thought of as less of a slippery slope than an ‘uphill struggle’ and that there is an increasingly apparent need for governance that responsibly incentivises research, if not deployment: research which allows each idea to progress to a point of sociotechnical maturity which allows for more informed decision making over whether they should be further researched, developed or deployed, under what conditions, and in what circumstances. This is not to say that concerns about a slippery slope should be dismissed, however, but rather that flexibilities be built into the sociotechnical systems as they develop (Collingridge, 1980).

Our groups converged on two general approaches to the governance of climate engineering R&D (see Table 2). Three of the governance approaches focussed on global governance, a ‘top-down’ approach whereby an international agreement would harmonise the conduct of research across countries. In contrast, five of the approaches focussed on principles and protocols, a step-by-step, ‘bottom-up’ approach to governance. The application of these approaches often differed by group and by the climate engineering idea under consideration. For BECCS, Group 2 envisaged a principles and protocols approach driven by local geopolitics, whereas Group 4 envisaged reaching global agreement on an effective carbon price. For DACS, both groups 1 and 3 envisaged reaching global agreement on an effective carbon price. For SAI, Group 3 envisaged reaching global agreement on the conduct of research, whereas Group 4 envisaged a principles and protocols approach driven by a coalition of the willing. For MCB, both groups 1 and 2 envisaged a principles and protocols approach, but while Group 1 envisaged the approach as being driven by a coalition of the willing, Group 2 envisaged it as being driven by local geopolitics. All groups were consistent in their view that self-regulation or moratoria were implausible.

The three visions of a global approach to governance are broadly in line with the most commonly advanced propositions in the academic literature. These include international consortia brokered and run by individual nation states proposed by Virgoe (2009); collaborations brokered and run by experts and national governments proposed by Benedick (2011); multilateral negotiations through the United Nations Framework Convention on Climate Change variously proposed by Barrett (2008), Lin (2009) and Zürn and Schäfer (2013), or the United Nations Convention on Biological Diversity proposed by Bodle et al., 2014; research evaluation by the IPCC variously proposed by Barrett (2008) and Zürn and Schäfer (2013); novel international institutions including an International Climate Engineering Agency proposed again by Zürn and Schäfer (2013), International Climate Engineering Research Review and Coordination Boards proposed by Morrow et al., 2009 and other novel international bureaucratic institutions and associated scientific advisory bodies, such as those proposed by Bodansky (1996) and Humphreys (2011); as well as more general calls for international agreements made by Olsen (2011).

The five visions of a principles and protocols approach, however, follow a quite different direction for governing climate engineering research. These visions of governance, whether through local geopolitics or coalitions of the willing, developed ideas of a variable geometry: of seeing the tackling of climate change in terms of local portfolios of actions whose make-up would be prompted by local values and interests. Such national geopolitical considerations would mean that not all inflection points in the assessment of a single climate engineering idea would be the same, and that there would be different inflection points on climate policy too. For example, India is currently moving towards a centralised model of bioenergy production while China is moving towards coal gasification. Both of these pursuits could be extended by using CCS technology and there could be substantial cobenefits in terms of air quality for Indian and Chinese cities. National narratives could therefore broaden out climate policy choices in ways similar to our study broadening out governance scenarios. Given the architecture of the Paris Agreement and its shift towards multipolar environmental governance then (Elliott, 2012), we might look for diverse national portfolios, or what we might term ‘geopolitical wedges’, as distinct to the sorts of technological wedges that have featured in the literature to date (cf. Pascala & Socolow, 2004). A number of general propositions for developing research and innovation have been advanced to such ends (e.g. Dilling & Hauser, 2013; Rayner et al., 2013; Stilgoe et al., 2013a,; Bellamy, 2016)

Concurrently, the groups identified the conditions under which they thought that governments might achieve the incentivisation of climate engineering research (see Table 2). Based around the envisaged global agreement on an effective carbon price, the policy instruments suggested for greenhouse gas removal ideas revolved around intervention in market processes by affecting the price of carbon. For BECCS, it also included direct government investment through funding research. For DACS, it included direct controls to regulate limiting the permissible level of carbon dioxide emissions and moral suasion through appeals to corporate social responsibility. For both sunlight reflection methods,

Table 2
A summary of envisaged approaches to governance and policy instruments for incentivising climate engineering R&D.

Climate engineering idea	Envisaged approach(es) to governance of R&D	Envisaged policy instrument(s) for incentivising R&D
Bioenergy with carbon capture and storage (BECCS)	- Principles and protocols of local geopolitics (Group 2) - Global agreement on carbon price (Group 4)	- Market process by affecting global carbon price - Government investment in R&D
Direct air capture and storage (DACS)	- Global agreement on carbon price (Groups 1 and 3)	- Direct controls to regulate limiting the permissible level of carbon dioxide emissions - Market process by affecting global carbon price - Moral suasion through appeals to corporate social responsibility
Stratospheric aerosol injection (SAI)	- Global agreement on research and deployment (Group 3) - Principles and protocols of a coalition of the willing (Group 4)	- Government investment in R&D
Marine cloud brightening (MCB)	- Principles and protocols of a coalition of the willing (Group 1) - Principles and protocols of local geopolitics (Group 2)	- Government investment in R&D

the only suggested policy instrument was direct government investment through funding research. This places a particular importance on understanding how policy makers and funders view climate engineering ideas and how they may set research priorities (Rayner, 2016; Himmelsbach, 2017; Peters & Geden, 2017). At the same time, other ‘incentives’ for research were discussed by the groups that included climate change impacts or crises and the development of other, less desirable climate engineering ideas. Such impetuses underscore the suggestion that climate engineering is unlikely to be carried out as a unitary or isolated pursuit and may be best pursued in tandem with complementary solutions to climate change or wider policy challenges (Healey, 2014). Further research is needed to understand the advantages and disadvantages of different policy instrument pathways.

A number of the findings from our study are consistent with and advance those of the existing literature on climate engineering foresight. These include several factors that participants thought would be significant in influencing the trajectories of R&D, including general technical limitations that might arise in the course of R&D and the harmful impacts that they may bring (GAO, 2011; Banerjee et al., 2013; Haraguchi et al., 2015; Low, 2017). The occurrence of environmental crises, in particular, is a common feature in climate engineering scenarios (GAO, 2011; Boettcher et al., 2015; Low, 2017); highlighted here as both catalysts for (e.g. extreme weather events, climate tipping points or an Arctic methane emergency) and inhibitors of (e.g. food shocks or captured gas leakages caused by R&D itself) R&D. To this list we can add the agreement of a favourable carbon price as a key catalyst for both BECCs and DACS, and its absence as a key catalyst for SAI and MCB. Interactions with R&D into CCS or other climate engineering ideas also surfaced as a key factor, with successes for CCS detracting from CDR and successes for CDR detracting from SRM and vice versa. Such factors might be usefully thought of as strategic ‘footholds’ in the uphill struggle, to be exploited or avoided as appropriate.

6. Conclusion

In this article we set out to explore how far climate engineering ideas may develop in the future and under what governance arrangements. Our scenarios revealed a plethora of challenges that recast the governance of climate engineering as less of a slippery slope than an uphill struggle. This suggests that a shift in the emphasis of policy goals may be in order, one in which governance intended to constrain research makes room for that which responsibly incentivises it. Our participants converged on two such governance models with policy instruments to match: a top-down, global governance approach and a bottom-up, principles and protocols approach. We contend that any responsible incentivisation of climate engineering research will consist of two chief tenets: (1) a pluralistic architecture of governance arrangements and policy instruments that attends to national differences as well as collective ambitions, and (2) that such architecture emerges from an inclusive and reflexive, and thereby legitimate, process that attends to diverse perspectives (cf. Bellamy, 2016).

Our study has substantially broadened out the diversity of perspectives, options considered and issues raised in the area of climate engineering foresight. It has broadened out to perspectives from developing as well developed countries and those from government, industry and civil society as well as academia. It has also taken account of climate engineering ideas other than stratospheric aerosol injection and resisted narrowly closing down on a small number of issues. Our recommendations for climate policy are plural and, as always, conditional on the methodological framings we have employed. While we have begun to develop an approach that better attends to epistemological diversities, there is much more work to be done. Other developed, and particularly developing countries need to be engaged through such exercises (cf. Winickoff et al., 2015). They also need to extend their reach beyond experts to diverse publics, who have already offered substantively distinct insights into other domains of climate engineering appraisal (Bellamy et al., 2016) and governance (Pidgeon et al., 2013; Bellamy et al., 2017). The problem framing too, must be expanded to account for alternative options for tackling climate change that are otherwise marginalised, spanning mitigation options and adaptation.

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